

Topological insulator particles as optically induced oscillators: towards dynamical force measurements and optical rheology

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We report the first experimental study upon the optical trapping and manipulation of topological insulator (TI) particles. By virtue of the unique TI properties, which have a conducting surface and an insulating bulk, the particles present a peculiar behaviour in the presence of a single laser beam optical tweezers: they oscillate in a plane perpendicular to the direction of the laser propagation, as a result of the competition between radiation pressure and gradient forces. In other words, TI particles behave as optically induced oscillators, allowing dynamical measurements with unprecedented simplicity and purely optical control. Actually, optical rheology of soft matter interfaces and biological membranes, as well as dynamical force measurements in macromolecules and biopolymers, may be quoted as feasible possibilities for the near future.

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Since the seminal papers by Ashkin and collaborators [1, 2], the optical trapping and manipulation of micrometer-sized particles have found applications in many areas, from interface and colloid science to single molecule biophysics [3–5]. Nowadays, a common optical tweezers setup consists of a laser beam focused by a microscope objective of large numerical aperture. This apparatus can trap dielectric objects near the lens focus, being a powerful tool to capture and manipulate particles with sizes at micrometer scale. The optical trapping of dielectric particles are based on the competition between radiation pressure, which occurs whenever light is reflected or absorbed by the particles, and gradient force, coming about from light refraction [6]. In general, stable trapping occurs whenever gradient force dominates, in such a way that the dielectric particles are kept around the laser beam focus [6]. Furthermore, optical trapping demands dielectric particles with refractive index higher than that of its surround medium (deionized water, $n \approx 1.33$, is used in most experiments). On the other hand, except for very special conditions, metallic particles cannot be stably trapped by optical tweezers [7–10].

In turn, topological insulators (TI's) are materials with unique properties, whose robust stability is topologically protected by time reversal symmetry. They are known to have insulating (dielectric) bulk, but conducting surface states that support charges flowing without dissipation. These states are characterized by a single gapless Dirac cone and exhibit the remarkable spin-momentum locking: a charge carrier moves in such a way that its momentum is always perpendicular to its spin [11–14]. By the way, curvature has been shown to deeply affect the physical properties of TI's. For instance, it is predicted that

spherical [15, 16] or toroidal TI [17] geometry renders a distinct photo-emission spectrum. In addition, the electromagnetic response of TI's is such that an external electric (and/or magnetic) field induces both, magnetization and polarization as well, the so-called topological magnetoelectric effect. As a direct consequence, whenever light comes onto a TI, reflected and refracted rays experience topological Faraday and Kerr rotations, respectively [11–14]. Furthermore, it has been recently predicted that the topological Kerr effect gives rise to a residual force perpendicular to the incident plane whenever light is shed onto a magnetically capped spherical topological insulator bead [18]. Such a topological-like force goes around some dozens of femtoNewtons, about the Casimir force scale [19]. Thus, whenever subjected to a highly focused light beam, like those used in optical tweezers, it is expected that a TI particle should experience competing effects coming from the interaction of light with its conducting surface and insulating bulk. We should wonder about the resulting effect of such an interaction to the TI-particle dynamics.

In this work, we conduct an experimental study regarding the optical trapping and manipulation of TI particles. By virtue of their special characteristics, these particles present a quite unusual dynamics under a highly focused light beam: they oscillate perpendicularly to the direction of laser propagation. In other words, they behave as optically induced oscillators, making them unique candidates to open an avenue for novel applications of optical manipulation techniques, allowing dynamical measurements with unprecedented simplicity. Actually, rheology of soft matter interfaces and biological membranes, dynamical force measurements in macromolecules and biopolymers may be quoted as some of feasible achievements by using TI-beads as optical oscillators.

The particles of Bi_2Te_3 and Bi_2Se_3 are topological insulators at room temperature and have been obtained by laser ablation technique (see details in the Supplemen-

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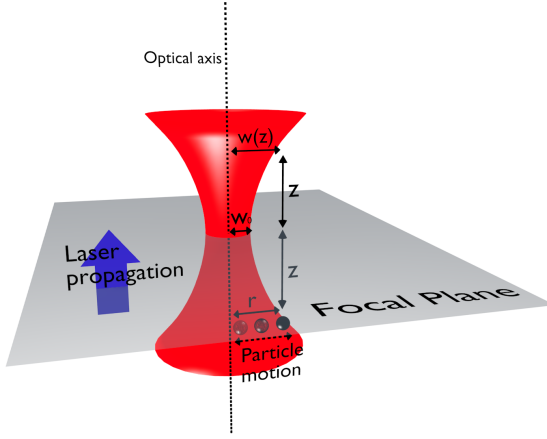


FIG. 1. (Color online) Experimental setup yielding the oscillatory dynamics and the relevant parameters. A TI particle is located around $z \sim 10 \mu\text{m}$ below the focal plane and it oscillates perpendicularly to the optical axis direction. The particle lies within the optical beam waist, i.e. $r(t) < w(z)$.

tary Material). Measurements were made for both composites and they present the same general behaviour. In order to be more succinct, we present here only the results for Bi_2Te_3 , which have a more spherical shape than the Bi_2Se_3 ones. For the optical experiment, we have selected only those particles with a nearly spherical shape, and average diameter between $3 \mu\text{m}$ and $7 \mu\text{m}$. Later, they have been suspended in deionized water and placed in the sample chamber, which consists of an *o-ring* glued in a microscope coverslip. The optical tweezers consist of a 1064 nm ytterbium-doped fiber laser (IPG Photonics) operating in the TEM_{00} mode, mounted on a Nikon Ti-S inverted microscope with a $100\times$ NA 1.4 objective. In all experiments we have used a laser power of 25 mW measured at the objective entrance.

Fig. 1 shows our experimental setup along with the relevant parameters. TI particles located $z \sim 10 \mu\text{m}$ below the focal plane have been observed to oscillate perpendicularly to the optical axis direction, say, parallel to the focal plane. On the other hand, if the particle is close enough to the focal plane ($z \lesssim 3.5 \mu\text{m}$), then radiation pressure becomes high enough to drift it away, like occurs to typical metallic particles. Here we propose a simple model that takes into account the competition between radiation pressure and gradient forces on TI particles. Such a model allows one to predict the resulting optical force on the particle yielding its oscillatory dynamics. At a certain vertical distance z from the focal plane ($z = 0$), the laser intensity at an arbitrary position (r, z) , normalized by the corresponding intensity at the optical axis ($r = 0, z$), can be written appropriately, for a Gaussian beam profile, by:

$$I_N = \exp\left(\frac{-2r^2}{w(z)^2}\right), \quad (1)$$

where $w(z)$ is the beam waist at position z ; it is related to the beam waist at the focal plane, $w(z = 0) \equiv w_0$, as below:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}, \quad z_R = \frac{\pi w_0^2}{\lambda}. \quad (2)$$

Since radiation pressure is proportional to the laser power, then we have:

$$F_{rp} = \mathcal{F}_{rp} \exp\left(\frac{-2r^2}{w(z)^2}\right), \quad (3)$$

where \mathcal{F}_{rp} accounts for the maximum magnitude of this force, at $r = 0$.

In turn, the gradient force, is given by:

$$F_g = -\frac{4rA}{w(z)^2} \exp\left(\frac{-2r^2}{w(z)^2}\right), \quad (4)$$

since F_g is proportional to the negative derivative of the beam intensity. The constant A is proportional to the maximum magnitude of the gradient force, \mathcal{F}_g , which occurs at $r = (1/2)w(z)$, by:

$$A = \frac{1}{2}\mathcal{F}_g w(z) \exp(1/2). \quad (5)$$

Finally, the resulting optical force $F = F_{rp} + F_g$ can be written as:

$$F = \left(\mathcal{F}_{rp} - \frac{2r\mathcal{F}_g \exp(1/2)}{w(z)}\right) \exp\left(\frac{-2r^2}{w(z)^2}\right). \quad (6)$$

In Fig. 2 it is shown how such forces behave as r varies. For that, we have taken: $w(z) = 5 \mu\text{m}$, $\mathcal{F}_{rp} = 4 \text{ pN}$ and $A = 10 \text{ pN}\cdot\mu\text{m}$, corresponding to $\mathcal{F}_g \sim 2.43 \text{ pN}$. For these parameters the resulting optical force is repulsive for $r < 2.5 \mu\text{m}$ and attractive for $r > 2.5 \mu\text{m}$. Indeed, the value of r where the crossover between repulsive and attractive regimes occurs is given by $r_c = \mathcal{F}_{rp}w(z)/2\mathcal{F}_g \exp(1/2)$. In addition, as long as $\mathcal{F}_{rp}/2\mathcal{F}_g \exp(1/2) > 1$, then $r_c > w(z)$, yielding only the repulsive regime, say, radiation pressure dominating over gradient force and no oscillatory motion taking place.

The procedure used to obtain the optical forces in the experiments is detailed in the Supplementary Material. Essentially, the bead position is recorded using videomicroscopy, from which other dynamical variables, like velocity and acceleration are readily obtained, as well as, the resulting force acting on the bead. Such a force comes from two independent contributions: the optical and the viscous (Stokes) force, acting in opposite directions. Actually, in order to obtain the resulting optical force for comparison with the theoretical model described above, equation (6), one needs to subtract the contribution coming from the viscous force, which was calculated using the instantaneous velocity of the particle. [Three movies

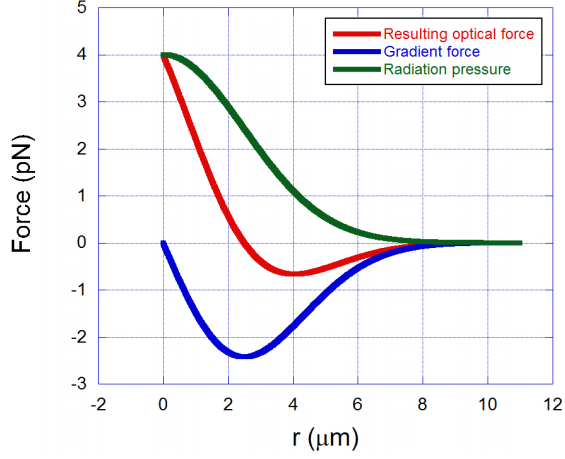


FIG. 2. (Color online) Theoretical behaviour of optical forces as functions of TI-particle position, r . Here, we have used the parameters $w(z) = 5 \mu\text{m}$, $\mathcal{F}_{rp} = 4 \text{ pN}$, and $A = 10 \text{ pN} \cdot \mu\text{m}$, corresponding to $\mathcal{F}_g \sim 2.43 \text{ pN}$.

showing the motion of Bi_2Te_3 TI-particles can also be found as a Supplementary Material].

In Fig. 3 it is shown the typical dynamics of the TI-particles, where its position relative to the optical axis, r , is plotted as function of the time, t . Such results have been obtained for a Bi_2Te_3 spherical-like bead with diameter $\sim 4.2 \mu\text{m}$ centered at $z \sim 10 \mu\text{m}$. The oscillations are well-defined in time with period $T \approx 3 \text{ s}$. Their amplitudes vary between $\sim 7 \mu\text{m} - 9 \mu\text{m}$, with closest approximation to the optical axis observed to be $\sim 3.2 \mu\text{m}$. In addition, the variation in the amplitudes comes from the fact that $r(t)$ only computes the motion parallel to the focal plane, whereas the particle position sometimes presents small fluctuations along z direction. Besides, once the TI particles are not perfect spheres, some deviations in the amplitude could be also associated to their shape. Fig. 4 shows the resulting optical force as a function of the particle position r for the attractive regime (particle approaching the optical axis). These example data have been obtained from the first oscillatory cycle shown in Fig. 3 (details in the Supplementary Material). In addition, it is noteworthy that our model fits the experimental data accurately, with the following values for the physical parameters: $w(z) = (5.55 \pm 0.15) \mu\text{m}$, $\mathcal{F}_{rp} = (4.1 \pm 0.6) \text{ pN}$ and $\mathcal{F}_g = (2.1 \pm 0.2) \text{ pN}$. For the other oscillatory cycles, the variations in the oscillation amplitude impart on the values of the optical forces \mathcal{F}_{rp} and \mathcal{F}_g , making them to vary from one cycle to the other, namely whenever very distinct amplitude cycles are considered. On the other hand, it is worthy to mention that the parameter $w(z)$ is very robust against amplitude variation, what is expected since $w(z)$ is a characteristic of the laser beam. Its average value, found considering different particle motions, reads $w(z) = (5.7 \pm 0.3) \mu\text{m}$. Taking $z \sim 10 \mu\text{m}$ to equation (2), yields $w_{0_{exp}} = (0.45 \pm 0.02) \mu\text{m}$, which is in good agree-

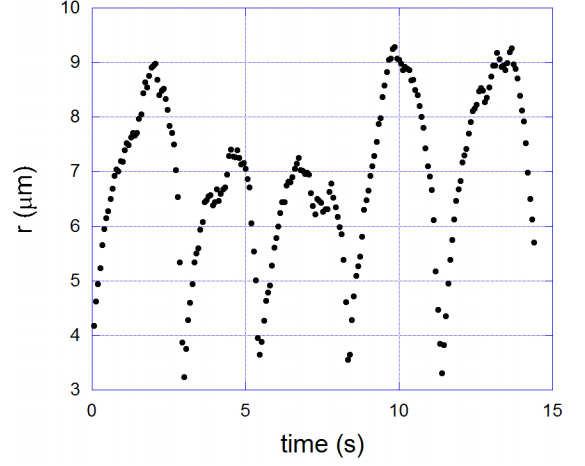


FIG. 3. (Color online) Typical dynamics of the TI-particles, $\mathbf{r}(\mathbf{t}) \times \mathbf{t}$. The particle position $r(t)$ is measured relative to the optical axis, at $r = 0$. This experiment was performed with a Bi_2Te_3 spherical-like bead with average diameter $\sim 4.2 \mu\text{m}$. The bead have been placed at $z \sim 10 \mu\text{m}$. The motion presents a well-defined frequency for the oscillations, with period $T \approx 3 \text{ s}$. The uncertainty in the measurement of position $r(t)$ is $0.017 \mu\text{m}$.

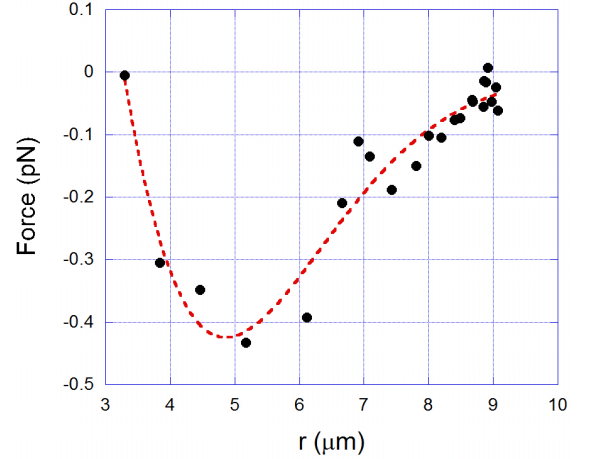


FIG. 4. (Color online) Resulting optical force as function of particle position \mathbf{r} . Here, the particle is moving towards the optical axis (attractive regime). Experimental data (*black circles*) are well-fitted by the theoretical model (*dashed line*), equation (6). The estimated mean uncertainty in the calculation of the force is 0.03 pN .

ment to the predicted value $2\lambda/\pi NA \sim 0.36 \mu\text{m}$ [20]. The repulsive regime, say, particle moving away from the optical axis, is discussed in the Supplementary Material.

Fig. 5 shows how the period of the oscillations depends upon beads diameter. Smaller beads tend to oscillate slower than larger ones. For instance, a bead with diameter $\sim 4.2 \mu\text{m}$ has a period $\sim 3.5 \text{ s}$ (frequency $\sim 0.3 \text{ Hz}$), while another with $\sim 6 \mu\text{m}$ has its frequency increased to $\sim 1 \text{ Hz}$. Although these oscillations are

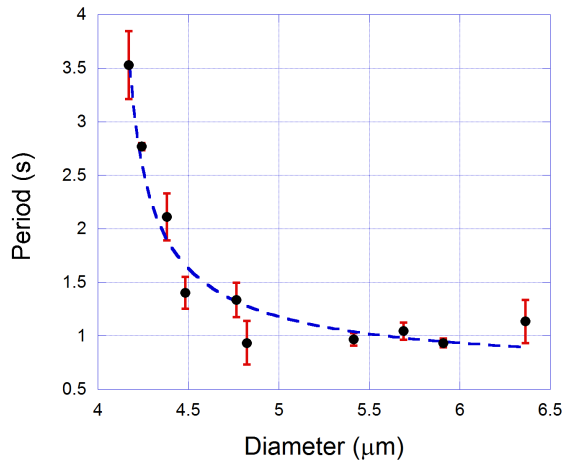


FIG. 5. (Color online) Period of the oscillatory motion as a function of the particle diameter. Experimental results (black circles) along with their respective errors (red bars). Note that as particle size increases the period diminishes in a way relatively well-described within the harmonic oscillatory regime (traced fitting curve).

not harmonic (recall the expression of the optical force, equation (6), along with the viscous dissipation), such a behaviour is well-captured within the simple harmonic regime, as follows. For that, recall that the gradient force comes from volumetric bulk refractions, then as particle radius, a , varies it is expected that $F_g \sim Aa^3$. Once radiation pressure increases with the particle area then $F_r \sim Ba^2$, while Stokes force goes like $F_S \sim Ca$, where A, B , and C are constants. Restricting ourselves to simple harmonic oscillatory description dictated by these forces, the period, $T = \sqrt{m/k}$ (spherical particle mass $m = 4\pi\rho a^3/3$) goes like $T \sim \sqrt{\frac{a^3}{Aa^3 + Ba^2 + Ca}}$. For the fitting depicted in Fig. 5 we have $T' \sim \sqrt{\frac{a^3}{A'a^3 + B'a^2 + C'a}}$, with $A' \sim 1.81 \text{ s}^{-2}$, $B' \sim 3.89 \text{ } \mu\text{ms}^{-2}$, and $C' \sim -46.50$

$\mu\text{m}^2 \text{ s}^{-2}$.

The important point to be stressed here concerns the actual possibility of tuning the particle period/frequency by just varying its size. Other improvements are certainly obtained by adjusting other physical parameters, like the beam power and so forth.

In summary, we have observed that microsized topological insulator Bi_2Te_3 particles oscillate perpendicularly to the optical axis whenever subject to a highly focused light beam. Even though the oscillations are not harmonic, the period/frequency appears to remain practically constant during a number of cycles. Such a frequency is also dependent on the particle size, increasing with the beads diameter in such a way well-described by a simple harmonic approach. Both of these features are important for practical purposes and they may be further improved by combining particle size/shape with modulated intensity/power laser beam. For instance, beads having more regular spherical shape are crucial for highly precise experiments. This precision is important to make such optically induced oscillators useful in dynamical force measurements in macromolecules and biopolymers. They may also play an important role in optical rheology of biological membranes and soft matter interfaces.

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